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An experimental investigation of combustion pressure oscillations in solid fuel ramjets.

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AN EXPERIMENTAL INVESTIGATION OF COMBUSTION
PRESSURE OSCILLATIONS IN SOLID FUEL RAMJETS

by

Ted Michael Parafiorito

March 1984

Thesis Advisor: D. W. Netzer

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The combustion efficiency of a vitiated air heater was also evaluated using a gas chromatograph to measure unburned fuel in the exhaust. Negligible unburned gaseous fuel existed for all fuel-air ratios and temperatures.

An Experimental Investigation of Combustion Pressure Oscillations in Solid Fuel Ramjets

by

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TABLE OF SYMBOLS

A	area
A^*	nozzle throat area
C_d	discharge coefficient
d	diameter
g_c	gravitational constant (32.2 ft-lbm/lbf-sec^2)
L	length
m	mass
$\dot{m}$	mass flow rate
P	pressure
P'	oscillatory pressure
R	gas constant
t	time
T	temperature
γ	ratio of specific heats
ΔW	weight change
η	efficiency
ρ	density

SUBSCRIPTS

a	air
aft	rear orifice plate
av	average
b	burn
be	burner exit

bp	bypass
c	chamber
C_2H_4	ethylene
ex	experiment
f	final, fuel
fav	final average
h	head
H	Helmholtz
htr	heater
i	inlet
iav	initial average
m	mixer
O_2	oxygen
p	fuel port
PMM	Plexiglas
pri	primary
r	reattachment
t	stagnation, total
th	theoretical, throat
ΔT	temperature difference

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I wish to acknowledge the help and patience of Professor David Netzer who provided elbow grease as well as theoretical assistance during the course of this series of experiments. A very special thanks also goes to Mr. Glenn Middleton, machinist extraordinaire, for his work and expert advice. I would also like to thank Mr. Pat Hickey, Mr. Ted Dunton, Mr. Bob Besel, and Mr. Ron Ramaker for their assistance and cooperation. I would also like to thank my friends Gillette and Marge for their sage advice and suggestions in the writing of this report.

I. INTRODUCTION

In recent years, our potential enemies have expanded an already large weapons industry in a military construction program of unprecendented magnitude. A new aircraft factory is built every two years and new weapons systems are perfected and produced with alarming regularity. On our side, up until recently, budget cuts and inflation have eroded an already austere military hardware procurement schedule. Even now, the recent rises in available funding for new weapons and weapon systems cannot reverse the atrophy in our military hardware industry overnight. It is of paramount importance that new weapons be as simple yet effective as possible to maximize our use of procurement funds.

Tactical missiles are facing newer, more sophisticated Soviet-bloc aircraft of increasingly higher performance. In the face of this demand, the solid fuel ramjet (SFRJ) has received renewed interest. The SFRJ is one of the simplest of all air-breathing engines with some distinct advantages over other air-breathers and rockets. One chief advantage is its inherent simplicity, with a commensurate decrease in components needed compared to other air-breathing systems. The SFRJ has no fuel tanks, fuel pumps, or fuel

control systems to run up costs and possibly malfunction. The solid fuel is cast or bonded in the motor case; with a fixed geometry inlet duct and a fixed exhaust nozzle, no other air-breathing engine is simpler. In comparison to rockets, the SFRJ does not carry all its oxidizer in its fuel, so it can package more fuel in the same volume with a correspondingly longer burn time and the ability to provide power-to-target over longer ranges. In short, fewer parts and easier, more efficient loading should result in both lower initial and life-cycle costs when compared to many other propulsion systems.

However, before the SFRJ can be used effectively, it must be demonstrated that it has reliable, efficient and consistent performance throughout the operational envelope of the proposed future missiles. Increased diffuser and combustion performance at high supersonic speeds indicates that the SFRJ is most likely to be considered for applications at these higher speeds, although it can, in principle, be used at high subsonic and low supersonic speeds.

The Naval Postgraduate School has been actively involved in SFRJ research since 1973. In 1981 Metochianakis, et al [Ref. 1] attempted to control combustion efficiency by altering the nearwall turbulence/mixing. During the course of those investigations it was found that lower performance (measured as lowered combustion efficiency) occurred when

combustion pressure oscillations were present. These pressure oscillations increased the fuel regression rate which effectively increased the equivalence ratio for the same fuel grain lengths and air flow rates. As a result, it was not possible to determine whether the decreased performance was due to the presence of combustion pressure oscillations or the increased equivalence ratio.

In 1982 Begley [Ref. 2] attempted to clarify the effects of air flow rate and combustion pressure oscillations on combustion efficiency, with Plexiglas (PMM) as a fuel. The tests were conducted in both bypass and non-bypass modes of operation. The non-bypass tests were conducted with high and low air flow rates, and in all cases there was stable combustion (no pressure oscillations present with amplitudes greater than 5% of operating pressure). The bypass tests were conducted with and without a sonically choked head-end and bypass inlets. The choked inlets effectively isolate the air feed system from the combustion process. Combustion pressure oscillations were present in all tests conducted without sonic chokes, with a frequency of 120 Hertz and peak-to-peak pressure variations greater than 10% of the average chamber pressure. It was found that fuel regression rates were approximately 10% above those obtained when a stable condition was present. Analysis of data from these bypass tests showed an overall

enhancement of the combustion process from the pressure oscillations when the fuel port equivalence ratio was near one (lean overall equivalence ratio). When the equivalence ratio was greater than one in the fuel port (an overall equivalence ratio near one) the combustion process was degraded. When sonic chokes were used in the primary air inlet, the combustion process was effectively isolated from the inlet ducting and pressure oscillations were eliminated.

In these earlier studies it was not possible to isolate that part (or parts) of the combustion process which was capable of coupling with the resonant frequency of the inlet air ducting. In addition, adequate instrumentation was not present to allow the mode(s) of oscillation (acoustic, bulk, etc.) to be determined. Some possible mechanisms which could be capable of causing periodic energy release are: 1) vortex shedding at the inlet dump plane or aft mixer dump plane, 2) shear layer or reattachment zone disturbances at the air inlet or aft mixing chamber inlet, and 3) mixing or chemical reaction rate variations in either the flame stabilization or boundary layer combustion regions. One expected driving mechanism for the disturbances is bypass air injection into the aft mixing chamber. The injection of this air into the main combustion flow is a source of turbulence/distortion. Previous cold flow

studies by Binn, Scott and Netzer [Ref. 3] have shown that these downstream disturbances can affect upstream conditions. Periodic disturbances of the shear layer reattachment zone by this bypass air injection could result in periodic energy release rates within some or all of the fuel port. These periodic energy release rates could then couple with the inlet air feed system acoustics resulting in sustained oscillations with large amplitudes. The SFRJ motor which has been used at the Naval Postgraduate School may have several different resonant frequencies near that of the observed oscillations. These include the Helmholtz or bulk modes, the first longitudinal acoustic mode, periodic vortex shedding and convective waves. Previous studies by Netzer and Katz [Ref. 4] have indicated that the vortex shedding frequencies for the inlet recirculation zone were significantly higher than the observed pressure oscillation frequencies, but that the shedding frequency for the aft mixer was only slightly higher than the observed frequencies.

In this investigation tests were conducted to help clarify the relationship between combustor geometry and combustion pressure oscillations. Tests were conducted with three dynamic pressure transducers mounted in the combustor so as to identify the frequency and mode of oscillation. The first test established a baseline configuration, after which one dimension of the combustor geometry was

changed for each succeeding run. By changing only one variable at a time and observing its effect on combustion pressure oscillations, the relationship between combustor geometry and combustion pressure oscillations was investigated.

Since ramjets are normally operated at high supersonic speeds the combustor inlet air temperature can be quite high, generally between 800°R and 1400°R. In connected pipe testing the hot air is often provided by using a vitiated air heater. However, a small amount of unburned fuel in the air heater can significantly affect the measured combustion efficiency of the SFRJ. It is, therefore, necessary to ensure efficient operation of these air heaters. A part of this investigation involved the calibration of the vitiated air heater located within the Naval Postgraduate School SFRJ test facility.

II. DESCRIPTION OF APPARATUS

A. RAMJET MOTOR

The ramjet motor used in this series of experiments has been used at the Naval Postgraduate School in the past for ramjet combustion research [Refs. 1, 2, 3 and 4] with a few minor modifications. Figure 1 is a schematic diagram of this SFRJ with pertinent physical dimensions listed. The head section contains a wedge to turn the incoming primary airflow 90 degrees and inlets for ethylene (used as an ignition fuel) and an igniter torch. In order to accurately measure the dynamics of combustion pressure oscillations, piezoelectric pressure transducers were installed as shown in Figure 2. The two transducers mounted in the aft mixer were installed 135 degrees apart. Another transducer was mounted to monitor air inlet pressure variations. The steady-state air inlet pressure and temperature were also measured.

The removable step insert was used to allow variation of the sudden expansion step height.

A cylindrically perforated polymethylmethacrylate fuel grain was used as the mid-section of the motor and was held in place by threaded rods between the head-end and aft mixer sections. A metal orifice plate was used at the

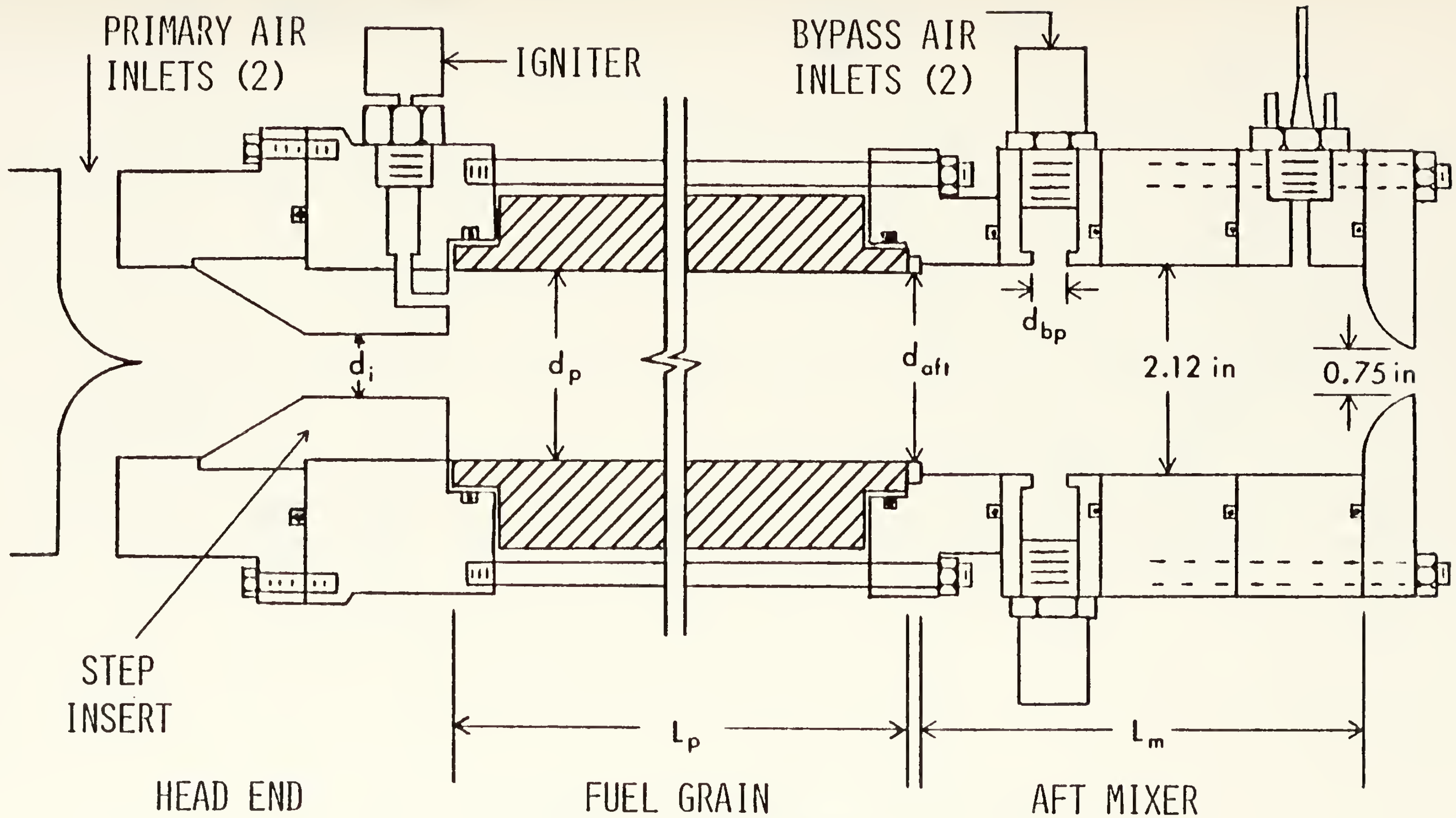

Figure 1. Schematic of Solid Fuel Ramjet Assembly.

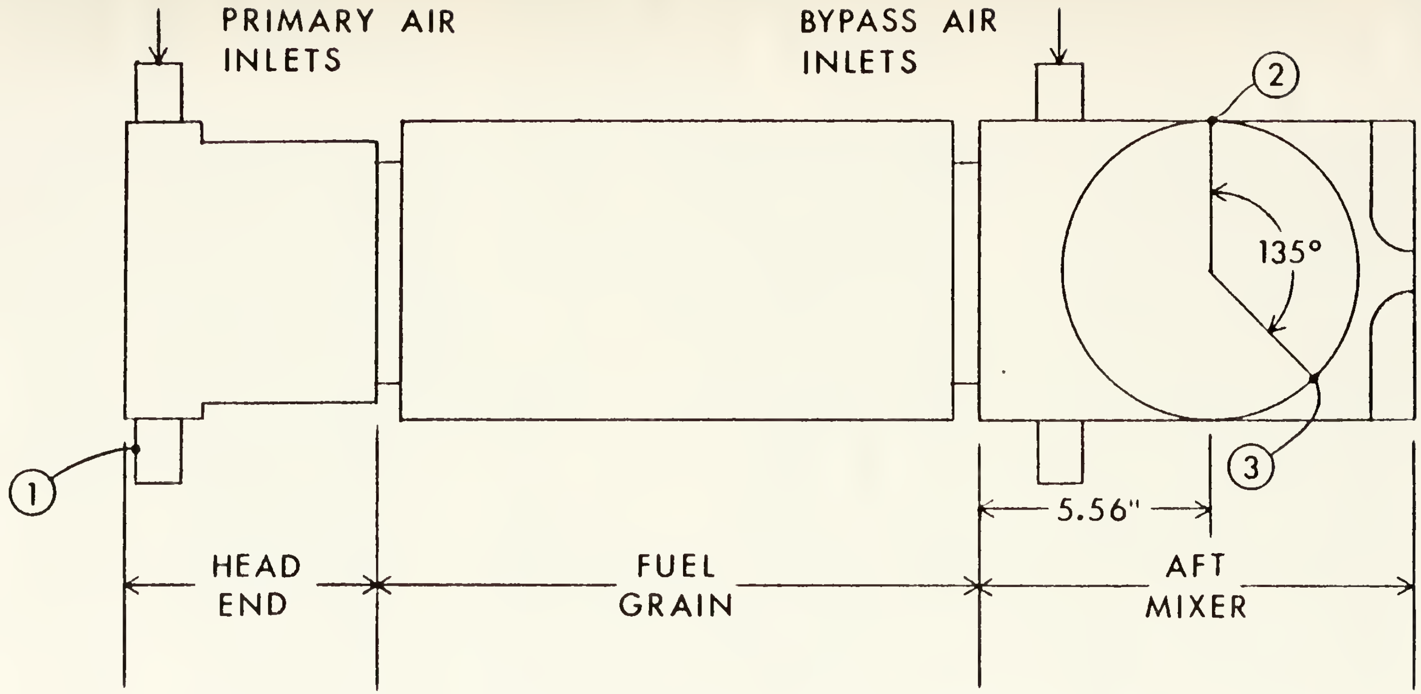

Figure 2. Transducer Locations.

end of the fuel grain to maintain a constant area ratio between the fuel port and the aft mixing chamber during combustion.

The aft mixing chamber was composed of stainless steel sections containing the bypass air inlets, a chamber pressure tap, and two piezoelectric pressure transducers. The mixer length could be varied by adding or removing sections. Pictures of the SFRJ assembly are shown in Figure 3.

B. AIR SUPPLY AND CONTROL SYSTEM

Figure 4 shows a schematic of the SFRJ air supply system. The remotely controlled pressure regulator is used to vary flow rates. Flow rates are measured by using sonically choked flow nozzles. The two electrically controlled pneumatically operated ball valves are used to vent the air flow to the atmosphere when required.

C. VITIATED AIR HEATER

The vitiated air heater used at the Naval Postgraduate School burns ethylene and incorporates an oxygen makeup supply (see Figure 4). Ethylene and oxygen flow rates are manually controlled by two sonically choked nozzles. Temperature and pressure are measured just upstream of the chokes and recorded during operation of the heater. A gas extraction tap is provided downstream of the heater to

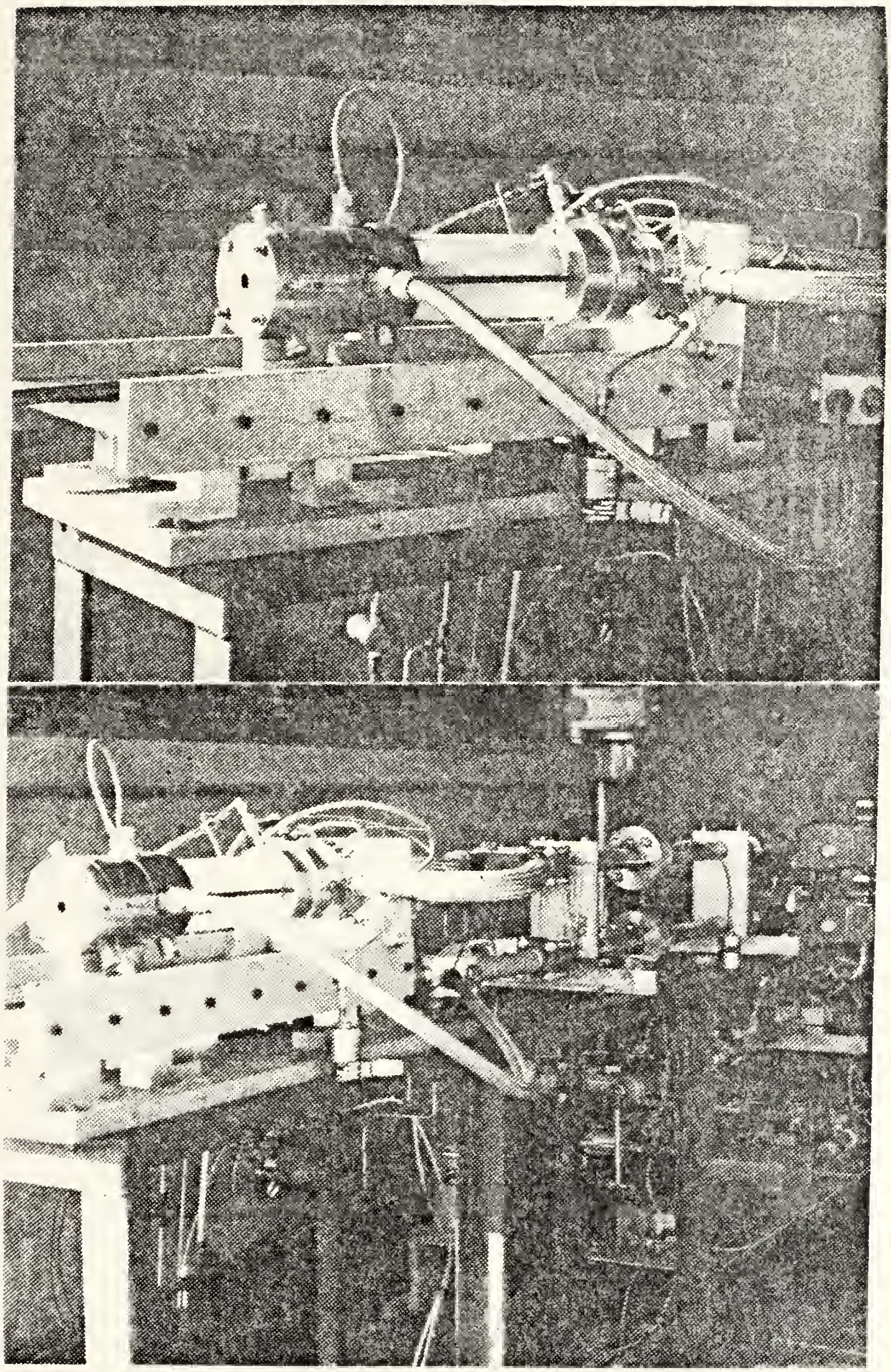

Figure 3. Photographs of Solid Fuel Ramjet Assembly

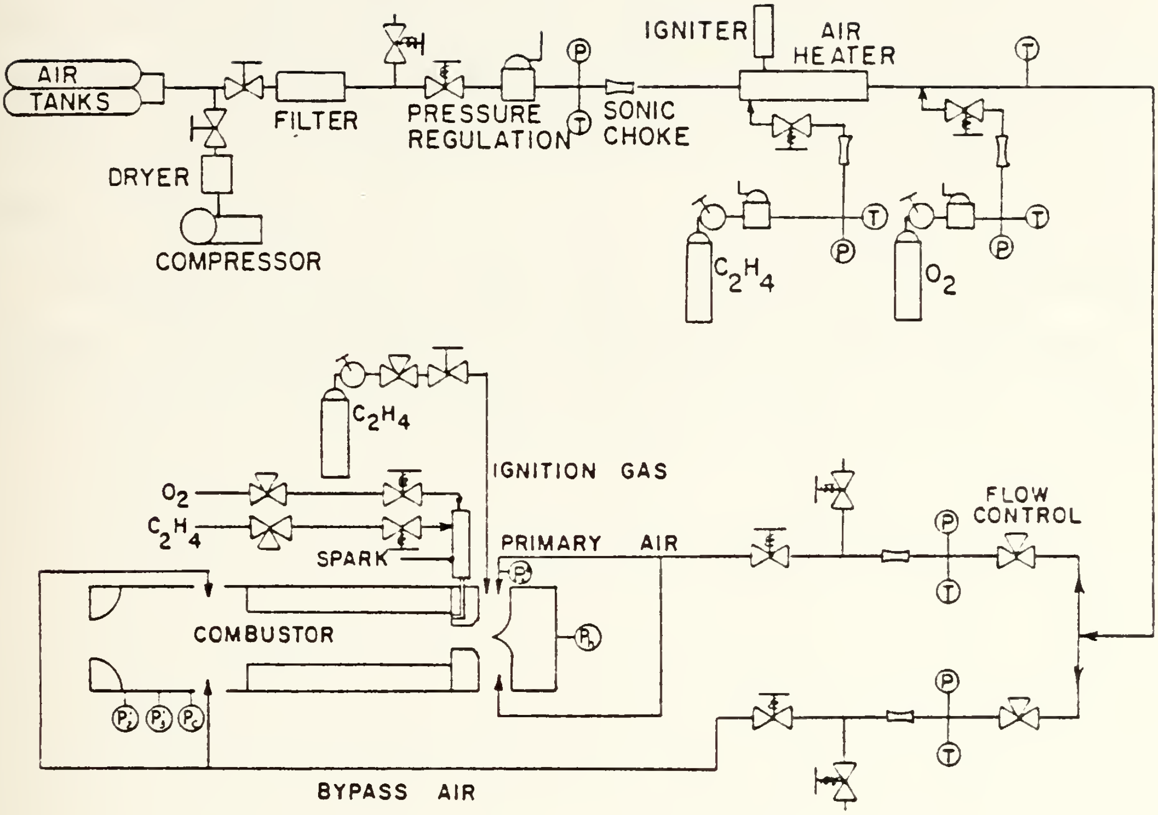

Figure 4. Schematic of Air Supply System.

supply an exhaust sample to a gas chromatograph. A series of chokes are available to allow operation of the heater throughout a temperature range of 800 to 1400 degrees Rankine and mainstream air flow rates of 0.1 to 3.0 lbm/sec. Two remotely controlled electric solenoid valves are installed between the sonic chokes and the heater to start and stop heater operation.

Vitiated air heater ignition is provided by an ethylene/oxygen torch downstream of mainstream ethylene injection. The torch is remotely operated and includes a spark igniter.

III. EXPERIMENTAL PROCEDURES

A. CALIBRATIONS

The transducers for the primary air line, bypass air line, and head and chamber pressures were calibrated over the expected ranges of operating pressures prior to each days runs with a dead-weight tester. The piezoelectric pressure transducers were calibrated before and after the test series and were found to be invariant.

B. DATA EXTRACTION

A Honeywell 1508B Visicorder was used to record $P_{t_{pri}}$ $P_{t_{bp}}$, P_h, and P_c. This recorder provided timing marks on the bottom of each trace during the run. A Honeywell 1508 Visicorder set to run at 80 inches per second was used to record the output from the dynamic pressure transducers in the inlet system and combustion chamber. A 100 Hertz signal was recorded at the bottom of each of the latter traces and was used as a frequency reference for data reduction.

Primary and bypass sonic nozzle pressures remained essentially constant during runs and were easily determined from the calibration data.

C. REACTING FLOW EXPERIMENTS

The air flow rate was set by the remotely operated dome loader shown in Figure 4. Downstream of this the air flow was split into two streams, primary and bypass, both selectable through the two remotely controlled gate valves. After this, both flows passed through the sonic chokes, where pressure and temperature were measured. The flow rate was calculated by

$$\dot{m} = C_d P_{t_a} \frac{\pi}{4} d_{th}^2 \sqrt{\frac{g_c \gamma}{R T_{t_a}} \left(\frac{2}{\gamma + 1}\right)^{\frac{\gamma+1}{\gamma-1}}}$$

where C_d was assumed to be 0.97.

An ethylene/oxygen torch was used in combination with an upstream ehtylene injection system to provide a source of ingition for the PMM fuel grains. Prior to ignition the desired air flow rate through the SFRJ was set using the remotely controlled pressure regulator. When the ignition switch was depressed both the torch and upstream ethylene were activated, typically for three to four seconds to ensure fuel grain flame stability. Each run was terminated by stopping air flow through the motor and purging the grain with nitrogen.

After each run was completed the fuel grain was removed, weighed and measured. By subtracting the final grain weight from the initial weight, the mass of fuel burned was

determined. The burn time of the run was found from the Visicorder trace and divided into the weight change to find the fuel mass flow rate.

In order to find the fuel regression rate a final average inside diameter was required. This was calculated using the grain length, initial inside diameter (measured prior to each run), and weight change by:

$$d_{fav} = \sqrt{\frac{4(\Delta W_f)}{\pi \rho_{PMM} L_p} + d_{iav}^2}$$

The average fuel regression rate was then calculated using

$$\bar{\dot{r}}_{av} = \frac{d_{fav} - d_{iav}}{2t_b}$$

In order to find the combustion efficiency an experimental stagnation temperature was first found using the one-dimensional, sonically choked flow equation:

$$T_{t_{ex}} = \frac{g_c \gamma}{R} \left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}} \left[\frac{C_d \bar{P}_c A^*}{\dot{m}_t}\right]^2$$

The temperature-rise combustion efficiency (based on measured combustion pressure) could then be found using

$$\eta_{\Delta T}(\%) = \frac{T_{t_{ex}} - T_{t_a}}{T_{t_{th}} - T_{t_a}} \times 100$$

$T_{t_{th}}$ was found using the NWC PEPCODE computer program (the adiabatic, equilibrium combustion temperature for the experimentally measured air temperature and fuel-air ratio).

D. VITIATED AIR HEATER

Before the vitiated air heater could be run it was necessary to determine the discharge coefficients of all the very small sonic chokes which had to be used. This was done by measuring the temperature and pressure upstream of the chokes and the mass flow rate downstream of the chokes using a Hastings-Teledyne mass flow meter. The discharge coefficient, C_d , was then calculated using

$$C_d = \frac{\dot{m}}{P_t \ \frac{\pi}{4} \ d_{th}^2} \sqrt{\frac{RT_t}{g_c \gamma} \left(\frac{\gamma+1}{2}\right)^{\frac{\gamma+1}{\gamma-1}}}$$

The discharge coefficient was calculated at a number of different flow rates and an average C_d was then determined.

To run the air heater at a given temperature and flow rate the necessary fuel-to-air ratio was found from the NWC PEPCODE computer program using ethylene and air (at the appropriate temperature) as the combustion ingredients. This fuel-air ratio was then multiplied by the air mass flow rate to find the necessary ethylene mass flow rate. The sonic nozzle upstream pressure was set to provide this

flow rate. The make-up oxygen mass flow rate required for stoichiometric combustion of the ethylene is

$$\dot{m}_{O_2} = 3.43\ \dot{m}_{C_2H_4}$$

The vitiated air heater combustion efficiency $\eta_{\Delta T}$ was found by

$$\eta_{\Delta T}(\%) = \frac{T_{t_{htr}} - T_{t_a}}{T_{t_{th}} - T_{t_a}} \times 100$$

The thirty-fold variation in flow rates over which the heater could be used presented a problem in regard to the unknown variation in heat loss to the pipe walls. A temperature was measured just downstream of the heater but it was not considered to provide a reliable average adiabatic exhaust temperature. A gas sample was therefore extracted from the flow just downstream of the stagnation temperature probe and sent to the gas chromatograph to ascertain the presence of any unburned ethylene in the heater output flow. The gas chromatograph employed was a Bendix Model 2200 Research Gas Chromatograph using two serially connected columns, one 1/8" x 6' with Porapak Q porous polymer packing (60/80 mesh) and the second 1/8" x 7' with Porapak R porous polymer packing (60/80 mesh). The carrier gas was helium and was used at a rate of 50 cc/min.

The detector was of the flame ionization type and the 2.0 ml sample was injected through a Carle manual valve. This model of chromatograph uses an oven temperature of 50°C.

IV. RESULTS AND DISCUSSION

A. INTRODUCTION

The method used to investigate SFRJ pressure oscillations was a series of logically planned tests. Table 1 shows the test plan for the bypass runs and Table 2 the plan for the non-bypass runs. The results of the series of experiments are tabulated in Tables 3 and 4 for bypass and nonbypass runs, respectively, and Table 5 presents a summary of observed combustion pressure oscillation characteristics.

B. PRESSURE OSCILLATIONS - BYPASS RUNS

Referring to Table 5, for the nominal case (test 1) a frequency of 126 Hz was observed which is approximately that of the first longitudinal acoustic mode for the inlet air system from the entrance to the motor to the primary line sonic choke. This frequency is much lower than the vortex shedding frequencies for the fuel grain and mixer, and the first and second longitudinal modes for the entire combustor, indicating that these were not primary modes of oscillation. It was possible that the instability could be a Helmholtz or other bulk mode of oscillation. The Helmholtz frequency for the air inlet system and combustor combination was close to the observed frequency. P'/P_c

TABLE 1

TEST PLAN - BYPASS RUNS

Variable	Condition*	f_H(Hz)**	X_r(in)	Purpose
Nominal	d_i=.502, d_p=1.5, d_{aft}=1.5 d_{bp}=.810, L_p=12.0, L_m=6.22	99	4.11	Establish baseline
Increase L_m	L_m=12.22	83	4.09	Change mixer volume
Increase L_p	L_p=18.0	88	4.12	Change combustor volume
Increase d_p	d_p=2.25	78	7.04	Increase shear layer length. Change recirculation zone volume. Increase combustor volume.
Increase d_p and d_i	d_p=2.25, d_i=.75	118	6.15	Increase shear layer length. Same h/d as nominal. Increase combustor volume.
Reduce d_{aft}	d_{aft}=1.0	144***	4.11	Isolate mixer from fuel grain.
Reduce d_{dp}	d_{dp}=.390	101	4.11	Increase bypass dump velocity.
Choked bypass		101	4.12	Isolate bypass feed system from combustor.

* All dimensions in inches.

** f_H= Helmholtz frequency for inlet and combustor.
f_{IL}=116Hz for air inlet system for all cases.

***f_H for inlet and fuel grain only.

TABLE 2

TEST PLAN - NON-BYPASS RUNS

Variable	Condition*	f_H(Hz)**	X_r(in)	Purpose
Nominal	d_i=.502, d_p=1.5, d_{aft}=1.5 L_p=12.0, L_m=6.22	100	4.09	Establish Baseline
Buried slot downstream of X_r	See Figure 5	100	4.09	Disturb boundary layer region
Enlarged d_p in recirculation zone	See Figure 6	88	7.04	Introduce minimum disturbance at X_r
Enlarged d_p in recirculation zone Enlarged d_i	d_i=.75 See Figure 6	132	6.15	Introduce maximum disturbance at X_r
Enlarged d_p in recirculation zone Enlarged d_i Choked inlets	d_i=.75 See Figure 6	***	***	Introduce maximum disturbance at X_r Isolate combustor from feed system

* All dimensions in inches

** f_H=Helmholtz frequency for inlet and combustor; f_{1L}=116 Hz for air inlet system for all cases.

***Unknown

TABLE 3

TEST RESULTS - BYPASS RUNS

EXPERIMENT	1	2	3	4	5	6	7	8
CONFIGURATION*	BP-UC	BP-UC	BP-UC	BP-UC	BP-UC	BP-UC	BP-CB	BP-UC
L_p (in)	11.81	11.89	18.20	11.84	11.96	12.02	11.87	11.80
L_m (in)	6.22	12.22	6.22	6.22	6.22	6.22	6.22	6.22
d_{inlet} (in)	.502	.502	.502	.502	.750	.502	.502	.502
d_p (in)	1.50	1.50	1.50	2.25	2.25	1.50	1.50	1.50
d_{aft} (in)	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
d_{bp} (in)	.810	.810	.810	.810	.810	.810	.810	.390
t_b (sec)	39.8	26.2	46.2	46.0	49.0	42.3	45.4	41.3
ΔW_f (lbm)	.6251	.3407	.9584	.8163	.9409	.5643	.5387	.5186
$\dot{m}_f$ (lbm/sec)	.0157	.0130	.0207	.0177	.0192	.0133	.0119	.0126
$\dot{m}_a$ (lbm/sec)	.207	.200	.202	.204	.205	.201	.204	.204
$\dot{m}_t$ (lbm/sec)	.223	.213	.222	.222	.224	.214	.216	.216
f/a	.076	.065	.103	.087	.094	.066	.058	.062
ϕ**	.627	.540	.850	.719	.778	.550	.483	.510
$\overline{P}_c$ (psia)	52.4	46.9	53.6	53.3	53.8	51.5	49.0	50.5
d_{fav} (in)	1.96	1.76	1.96	2.67	2.72	1.91	1.90	1.89
$\bar{r}$ (in/sec)	.00574	.00502	.00491	.00455	.00483	.00485	.00438	.00468
T_{th} (°R)	3187	2904	3857	3486	3662	2938	2700	2797
T_{ex} (°R)	2702	2389	2832	2814	2812	2845	2550	2681
$\eta_{\Delta t}$ (%)	82.0	78.5	80.6	77.5	73.1	96.2	93.2	94.9

* BP-UC - Bypass, unchoked
BP-CB - Bypass, sonic chokes in bypass feed lines
** f/a stoich. = .121

TABLE 4

TEST RESULTS - NON-BYPASS RUNS

EXPERIMENT	9	10	11	12	13
CONFIGURATION*	NBP-UC	NBP-UC	NBP-UC	NBP-UC	NBP-CI
L_p (in)	11.99	11.87	11.84	11.84	11.84
L_m (in)	6.22	6.22	6.22	6.22	6.22
d_i (in)	.502	.502	.502	.75	.75
d_p (in)	1.50	1.50	* * *	* * *	* * *
d_{aft} (in)	1.50	1.50	1.50	1.50	1.50
d_{dp}** (in)	-	-	-	-	-
t_b (sec)	46.7	40.6	47.0	33.2	12.5
$\bar{P}_c$ (psia)	60.5	59.1	63.7	58.4	57.2

* NBP-UC - Non-bypass, unchoked.
NBP-CI - Non-bypass, chokes in primary air inlet lines.
** Bypass dumps blocked off for non-bypass runs.
***Fig. 6 shows initial grain dimensions. Runs 12 and 13 used same grain as run 11 in successive firings.

TABLE 5

PRESSURE OSCILLATION CHARACTERISTICS

	TRANSDUCER NUMBER						
	1**		2**		3**		
EXP. NO.	$\frac{P'}{P_c}$(%)	freq. (Hertz)	$\frac{P'}{P_c}$(%)	freq. (Hertz)	$\frac{P'}{P_c}$(%)	freq. (Hertz)	
1	7.6	126	51.5	126	43.9	126	Control configuration.
2	2.2	121	12.3	121	-	-	Mixer lengthened 6in.
3	5.6	121	47.8	121	44.3	121	Fuel grain lengthened to 18in.
4	5.8	122	-	-	37.0	122	Fuel port enlarged to 2.25in. (h/d=.388) Transducer 2 not used.
5	23.4	126	51.0	126	53.9	126	Fuel port enlarged to 2.25in. and inlet diameter=.75in (h/d=.333).
6	10.8	131	42.9	131	37.5	131	Rear orifice plate reduced to 1in.
7	3.5	120	34.7	120	29.2	120	Sonic chokes in bypass lines only.
8	7.4	126	32.6	126	37.0	126	Reduced bypass dump port diameter to .390in.
9	-	-	5.1	114	4.3	114	Non-bypass run. Stable with small oscillations. Transducer 1 showed noise only.
10	1.6	-	1.9	-	3.2	-	Non-bypass with slot. Stable. (See Fig. 5.)
11*	1.2	122	4.5	122	5.1	122	First 6in. of grain enlarged to 2.25in. Inlet diameter=.502 (h/d=.388) See Fig. 6
12*	6.2	101	4.3	101	10.7	101	Same as run 11 but with inlet diameter of .75in. (h/d=.333).
13*	4.7	100	1.8	100	3.3	100	Sonic chokes in air inlet lines.

* Runs 11, 12 and 13 used same fuel grain in successive firings.
**See Figure 2 for locations.

was approximately 52% in the chamber and 7.6% in the primary air inlet line. The three measurements of the oscillatory pressure were in phase, indicating a bulk mode of oscillation. In test 2, the mixer was lengthened by six inches. The observed frequency was the same but P'/P_c was much lower (12.3% in the chamber and 2.2% in the air line). Lengthening the mixer would lower the Helmholtz frequency for the air inlet system and combustor combination by 16% but the observed frequency was the same indicating some other bulk mode was affecting the combustion process. It should be noted that increasing the mixer volume by a factor of two should decrease the effect of bypass dump port disturbances on the upstream flow within the fuel grain. Next (test 3) the fuel grain was lengthened by six inches, thus increasing the combustion chamber volume and significantly changing the fuel-air ratio. The frequency and amplitude were approximately the same for the nominal case, indicating that the bulk mode was probably not related to the boundary layer combustion region. In test 4 an increased grain internal diameter was used and resulted in approximately the same frequency and amplitudes as the nominal case. This test had a larger recirculation zone and shear layer length, and the lack of correlation of these two variables on the observed instability should be noted. Test 5 utilized a larger inlet diameter and a larger fuel port

diameter. The oscillations observed here were of the same frequency as the nominal case but P'/P_c in the chamber was slightly higher and P'/P_c in the inlet line was much higher. The larger inlet would be expected to permit increased coupling between the combustor and the inlet line. In test 6 the rear orifice plate diameter was decreased in an attempt to decrease the influence of mixing chamber disturbances on fuel port flow. The result was a slightly higher oscillation frequency and a slight reduction in the amplitude of the oscillations, indicating less coupling. Perhaps more significant was the observed increase in combustion efficiency, an apparent result of increased mixing near the aft end of the fuel grain. Tests to this point indicated that one possible driver was induced disburbances to the reattachment flow within the fuel port. In test 7 the bypass air lines were choked at the entrance to the motor. The observed frequency was slightly lower and the amplitude of the oscillation was lower, indicating the bypass lines had a small effect on the oscillations. However, the resonant frequencies of the bypass feed system did not couple with the combustion process. The last bypass test (number 8) used smaller bypass dump diameters, which raised the velocity of the bypass air entering the mixer. The frequency of the oscillations was the same as the nominal case but the amplitude was slightly lower,

implying the bypass air inlet velocity had little effect on the disturbances transmitted upstream. In both tests 7 and 8, increased dump velocities significantly increased the combustion efficiency without significantly affecting the instabilities. This result indicates that heat release rates near the grain exit and/or in the aft mixing region were not responsible for the oscillatory combustion.

At this point it was known that the oscillations were of a bulk mode, that they involved coupling with the primary-air inlet feed system and not the bypass feed system. It was also known that the volume of the recirculation zone, the magnitude of X_r, and the volume of the fuel port had no large effects on the frequency or amplitude of the oscillations. The volume of the aft mixer, however, had a large effect on the oscillations, indicating the initiating disturbance might be the bypass air dumps. One plausible explanation of the oscillations is that the bypass flow causes disturbances which are transmitted upstream to the flow reattachment zone. The resulting oscillations of the reattachment zone could readily cause oscillatory combustion in the flame-holder recirculation zone volume and/or in the turbulent boundary layer diffusion flame that develops downstream of flow reattachment. This oscillatory energy release can then couple with the inlet feed line acoustics.

Based on this proposed mechanism, the next series of tests were done to examine mechanisms for reattachment zone disruption other than bypass air.

C. PRESSURE OSCILLATIONS - NON-BYPASS RUNS

Table 4 shows the physical dimensions of the combustor/ fuel grains and the resulting chamber pressures and burn times. Pressure oscillation characteristics are shown in Table 5. These tests were concerned with induced disturbances to the reattachment zone in the fuel port using a non-bypass combustor which, historically, is stable. First a nominal test (number 9) was run and, as expected, resulted in stable combustion. A low amplitude 114 Hertz oscillation was present in the combustor, but only random noise was observed in the primary air inlet line. In test 10 a thermocouple instrumented slot was buried in the fuel grain (see Figure 5), into which the reattachment zone was supposed to burn midway through the run. However, the slot was inadvertently placed downstream of X_r, resulting in more of a disturbance to the boundary layer combustion region than to the reattachment zone. This resulted in stable combustion. In test 11 the fuel grain was enlarged for the first six inches of its length (see Figure 6). This increased the volume of the recirculation zone but the length of the enlargement was less than X_r. This resulted in random short bursts of 122 Hertz oscillations of low amplitude.

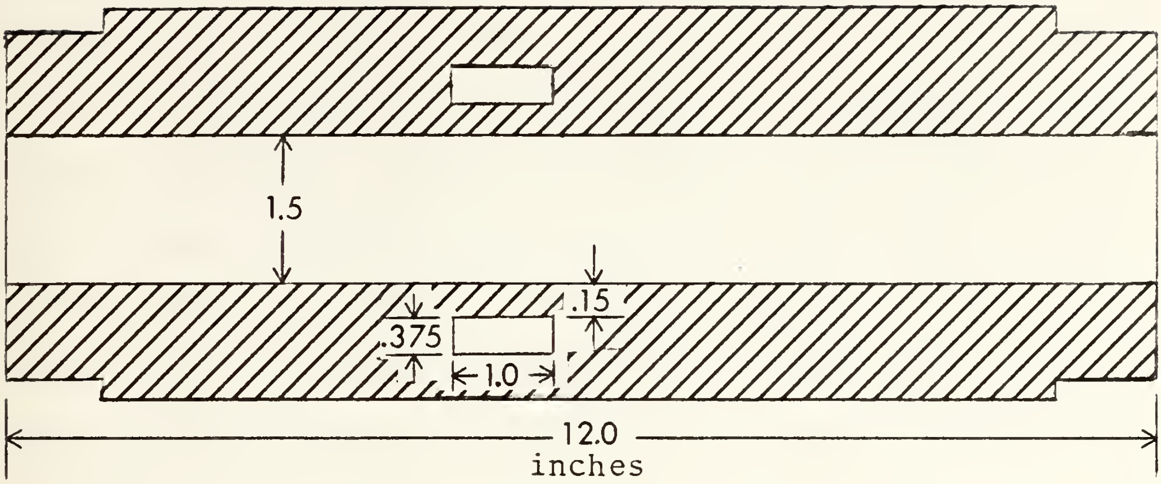

Figure 5. Fuel Grain with Slot.

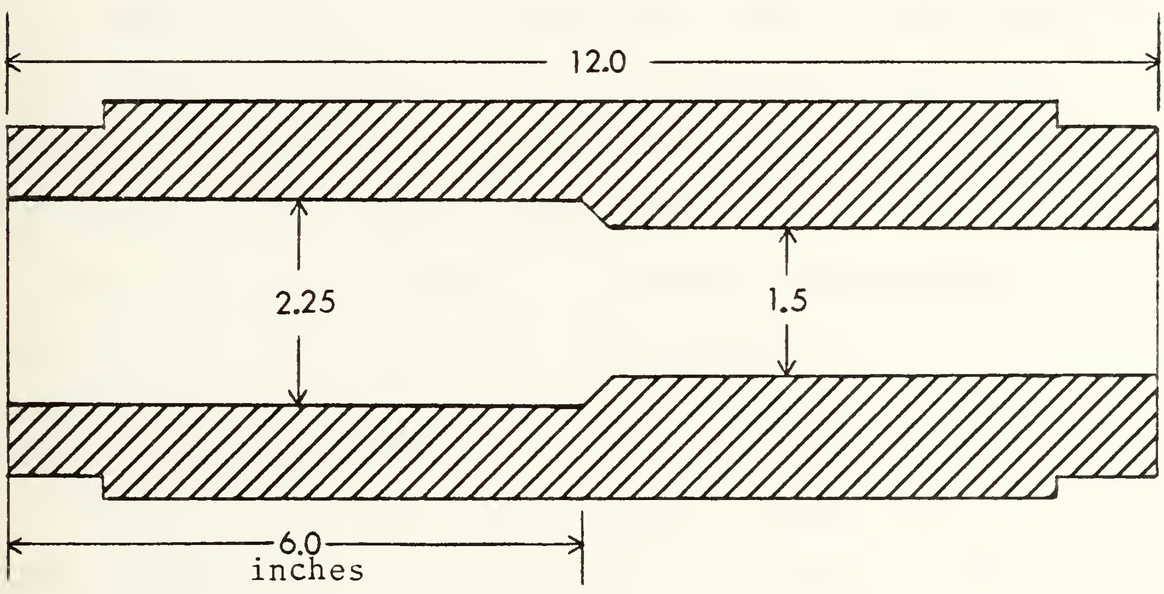

Figure 6. Partially Enlarged Fuel Grain.

In run 12 the same fuel grain was used but with a step insert of 0.75 inches. This put the lip of the enlargement at X_r. The result was a low amplitude instability of nominal frequency in both the combustor and air ducting. Test 13 used the same fuel grain, but with sonic chokes in the inlet feed lines. The combustion was essentially stable, indicating that disturbances of the reattachment region flow/combustion couples with the inlet feed system resulting in bulk mode oscillations in the combustor. The magnitude of the unsteadiness in the reattachment region is apparently insufficient in a nominal non-bypass flow environment to affect the overall combustion process or to couple with the inlet acoustics. Some external disturbance is necessary in order for the overall combustion process to be affected. Direct disturbances at the wall resulted in small oscillations while a larger disturbance to the zone (i.e., bypass air injection downstream) resulted in large amplitude oscillations.

D. VITIATED AIR HEATER

Table 6 shows the discharge coefficients for the sonic nozzles used in the vitiated air heater. During the calibration process it was found that the plumbing downstream of the sonic nozzles had restrictions that were close in size to that of the larger nozzles, resulting

TABLE 6

DISCHARGE COEFFICIENTS FOR SONIC NOZZLES

d_{th}	.020	.0292	.040	.052	.0595	.067	.076
C_d^*	1.033	1.093	.960	1.094	.972	.913	.529**

* installed values
**installed C_d low due to small diameter tube downstream of choke.

in calculated discharge coefficients in the .5 to .6 range. The setup was changed and the nozzles moved downstream to just in front of the point where ethylene was injected into the heater. The discharge coefficients shown are installed values. Table 7 shows the results of the air heater calibration tests. A pressure gauge was installed in the burner after the first four runs in order to assure that the ethylene sonic nozzle was properly choked. As discussed above, temperature rise combustion efficiency could not be accurately calculated due to the varying heat loss with flow rate and temperature. However, the gas chromatograph results (Table 7) indicated that a maximum of 17.4 ppm (by mass) of unburned ethylene existed in the exhaust gases. The NWC PEPCODE computer program was then used to determine the effect that this unburned ethylene would have on the combustion efficiency of the SFRJ. A

TABLE 7

AIR HEATER TEST RESULTS

RUN #	$\dot{m}_a$ (lbm/sec)	f/a	T^*_{htr} (R°)	P_{htr} (psia)	PPM C_2H_4	COMMENTS
1	.201	.0050	888	-	-	Unchoked C_2H_4 nozzle
2	.200	.0101	1331	-	.88	
3	-	-		-	-	No ignition
4	.499	.0059	966	-	4.35	
5	.497	.0099	1300	67	0.97	Installed P_{htr} gauge
6	.498	.0102	1430	75	1.08	
7	1.004	.0053	918	110	17.42	Marginally choked C_2H_4 nozzle
8	1.008	.0092	1210	133	1.28	
9	1.010	.0119	1446	145	3.42	
10	1.960	.0070	995	110	1.50	
11	1.966	.0060	905	107	2.66	
12	1.962	.0123	1588	135	4.46	
13	2.604	.0059	895	95	3.45	
14	2.520	.0010	1195	110	0.40	
15	2.473	0105	1338	105	13.9	

*approximate

change of only one degree would result in the theoretical temperature for the SFRJ burning PMM with unburned ethylene present in the maximum amount found. This would result in no measurable change in combustion efficiency.

V. CONCLUSIONS AND RECOMMENDATIONS

A. SOLID FUEL RAMJET

The apparent cause of the bulk mode pressure oscillations which couple with the inlet feed system acoustics was bypass air induced disturbances to the reattachment zone at the inlet dump. Any changes to the geometry that would tend to decrease disturbances introduced by bypass air injection can be expected to reduce oscillatory behavior in a system where the air inlet system is not isolated from the combustor.

B. VITIATED AIR HEATER

The vitiated air heater at the Naval Postgraduate School functioned properly and produced air with only trace amounts of unburned ethylene. The amounts of this unburned fuel were low enough to have no effect on the combustion of PMM and vitiated air (in the solid fuel ramjet installed downstream of the heater) throughout the range of equivalence ratios used in the SFRJ.

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